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A Biological and Physical Monitoring Program to Evaluate Long-term Impacts from Sand Dredging Operations in the United States Outer Continental Shelf

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ABSTRACT

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The Minerals Management Service (MMS) International Activities and Marine Minerals Division is charged with management of Federal Outer Continental Shelf (OCS) sand and gravel resources that would be used for beach nourishment to repair storm damage and protect against sea-level rise. To reduce environmental damage associated with long-term and large-scale use of these resources, a project was funded by MMS to design a comprehensive physical and biological monitoring program for sand-mining activities. An initial task of this project was performance of a literature review to determine where information gaps existed regarding the effects of sand mining and which physical processes and biological resources should be the focus of monitoring. Based upon the literature review and a conference with other investigators, the monitoring program was designed to include the following elements: benthic communities and their trophic relationships to fishes, marine mammals and wildlife (operational monitoring), sediment sampling and analysis, wave monitoring and modeling, bathymetric and substrate surveys, and shoreline monitoring and modeling. Protocols were developed for these elements to ensure consistency of methods among studies. The two primary physical impacts of concern are changes to the sea bed resulting in changes to the erosion and sedimentation processes along the shore and changes to the sea bed that would have a direct and significant impact on the biological environment. The most important biological impacts from dredging to be monitored in this program are changes in benthic secondary production and trophic transfer to fishes.

ADDITIONAL INDEX WORDS: *Sand resources, OCS, marine biological monitoring, marine physical monitoring, sand mining, benthic secondary production, trophic transfer, marine mammal monitoring.*

INTRODUCTION

Sand from nearshore coastal marine deposits has been frequently used for replenishing beaches in many, highly eroded, coastal areas of the United States, predominantly occurring along the East and Gulf Coasts of the U.S. Local and Federal agencies have relied on sand deposits in the territorial seas to restore the beaches and prevent further erosion, loss of property, and ecological damage. As these nearshore coastal deposits become depleted, sand sources located farther offshore on the Outer Continental Shelf (OCS) are being used. The Minerals Management Service (MMS) International Activities and Marine Minerals Division (INTERMAR) is charged with the responsibility for administering the Department of the Interior's role in mineral resource development other than oil, gas, and sulfur on the OCS. Between 1995 and 2001, MMS conveyed 14,600,000 cubic yards of OCS sand for ten projects.

MMS anticipates that OCS sand deposits will be needed as long-term sources of sand for coastal erosion management because there are diminishing supplies of onshore and nearshore sand. Long-term sources of sand are needed to address the effects of sea level rise and other natural and human-induced factors that lead to increased erosion. The renourishment cycles for beaches or coastal areas and the emergency repair of beaches from severe storms requires quantities of sand that currently cannot always be satisfied from state sources.

To prepare for an increased demand for OCS sand, the MMS has entered into cooperative agreements with ten coastal states to identify and study potential OCS borrow sites. They have also funded baseline marine biological and physical oceanographic environmental studies at select sites, and studied the potential impacts of sand dredging, including modeling studies, to determine the risk of shoreline erosion as a result of sand dredging. To date, coastal erosion management projects utilizing Federal OCS sand resources have been examined on a case-by-case basis. In the future, these resources will need to be managed on a long-term, large scale, system-wide basis to ensure that environmental damage will

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not occur as a result of continual and prolonged use. Sand sources that are to be used repeatedly may require additional biological and physical monitoring to ensure that unacceptable impacts to the marine and coastal environments do not occur. The MMS commissioned a study to design a long-term monitoring program that would evaluate the physical and biological changes that might occur as a result of using Federal OCS borrow areas, which is presented here. Readers are referred to MICHEL et al. (2001) for detailed sampling and analysis protocols for this program.

MONITORING PROGRAM GOALS AND ASSUMPTIONS

During the initial stages of the program, project goals and resource management questions that the monitoring program would address were developed. This effort was conducted with the assistance of MMS project personnel. Program goals included: to better understand the physical and ecological effects of sand dredging at the dredge site; and to obtain data or information that would be valuable for resource management decisions.

There were specific resource management questions around which the monitoring program was designed. First, is there a threshold above which continuous mining results in unacceptable damage/impairment to marine ecosystems? Second, are there operational methods that can be changed to reduce/eliminate negative impacts to physical or biological conditions? Third, does sand dredging result in predicted impacts? Fourth, are there impacts that were not predicted or anticipated? Fifth, do the predicted impacts occur and recover as expected?

Finally, to keep the focus of the monitoring program on locations where environmental impact assessments had indicated that sand dredging would be environmentally acceptable, the monitoring program design was based on several assumptions that concerned the type of dredging operations and locations where sand dredging would be allowed in the OCS. First, only beach replenishment type mining would be considered, in which only a small fraction of the material dredged is returned to the sea during dredging (less than 10 to 20% of what is taken on board). Second, dredging near environmentally sensitive (hard bottom, coral reefs, contaminated sediments) or culturally important locations would not be allowed by MMS; avoidable physical and biological impacts (critical habitats, locations and time periods) would be avoided. Third, the monitoring program would focus only on physical changes to habitat and community structure. Fourth, to determine the scale of monitoring efforts, it was assumed that the dredging projects subject to the monitoring protocols typically would involve removal of approximately 1,000,000 m^3 of sand.

The monitoring program had to be designed to address issues associated with the most common type of sand deposits identified by MMS, while also being applicable to other types of deposits. Ridge and shoal features represent the predominant morphology of the OCS sand borrow sites identified in MMS jurisdictions along the eastern seaboard of the U.S. Currently the only exceptions are identified deposits off the coasts of Florida and South Carolina. Nevertheless, it should be noted that the proposed protocols and monitoring program design are equally applicable to flat, shelf-type ecosystems where buried geological features can represent suitable sand and gravel borrow deposits. However, these deposits are more difficult to find and this may explain why most deposits identified thus far have been ridge and shoal features.

ENVIRONMENTAL IMPACTS FROM OCS SAND MINING

A comprehensive literature review was completed of the many studies of dredging in the continental shelf environment. As noted above, the MMS has sponsored many investigations of impacts along the Atlantic and Gulf coasts of the US and in the UK. Significant independent work on assessing impacts has also been completed in Florida, South Carolina, the UK, continental Europe and Hong Kong (MICHEL et al., 2001).

Following the completion of the literature review, those ecological resources (physical and biological) were identified that would have the greatest potential for being affected by offshore sand mining, both directly and indirectly. Impacts occurring as a one-time dredging event at a given location or as repeated dredging of an area over some time period were included. All physical and biological processes were initially considered.

Figure 1 illustrates the complex relationships between key physical and biological parameters that were identified during the literature review. Parameters are divided among one biological and three physical components, as well as geographic influences. Clearly, it would not be feasible to develop monitoring protocols to address all of the different processes and parameters represented in Figure 1. The challenge of developing the protocols was to take advantage of the interrelationships between processes in order to focus on some key indicator parameters, in addition to those that are most significant in nature. Table 1 presents a summary of the specific physical processes and biological communities potentially affected by OCS sand dredging, as identified during the literature review.

Impacts were defined as either direct or indirect. Direct impacts were defined as changes that occur as a primary response to the dredging process, without an intervening process (*e.g.*, removal of infauna). They generally extend from the area of extraction to the edge of the plume sedimentation footprint and/or extent of the plume itself in the water column. Indirect impacts were defined as changes that occur as a result of a secondary response to dredging activities (*e.g.*, change in fish populations because of the removal of infauna, changing the prey base), both within and outside the dredged area.

Geophysical Environment and Processes

There are three primary components of the physical environment: morphodynamics, seabed composition and oceanographic conditions. The term morphodynamics is used to describe the fluctuations and trends in changes to the elevation of the seabed and land surface extending from the vicinity of

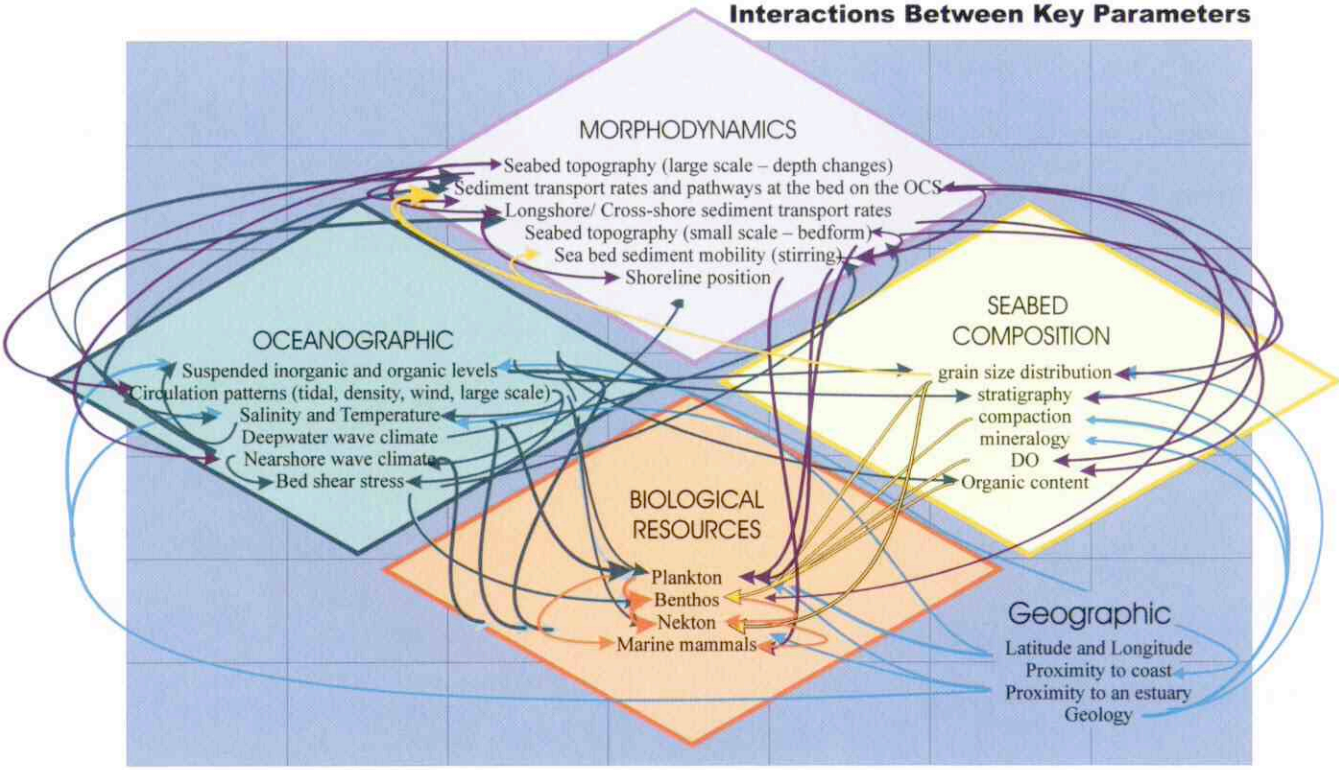

Figure 1. Interactions between physical and biological parameters.

the borrow deposit to the furthest onshore extent of the dynamic beach zone. These changes are a result of sediment transport processes, and may occur across a wide spatial scale, extending from individual sand grains, to bedform, to large-scale erosion and accretion, including shoreline change.

Seabed composition is the term used to address the temporal and spatial (three-dimensional) variability of the characteristics of the seabed including, but not limited to, grain-size distribution, stratigraphy, compaction, mineralogy, dissolved oxygen, and organic content. There are interrelationships between morphodynamics and seabed characteristics as the movement of sediment results in disturbance and change to the bed conditions and the sediment and larval deposition environment of the seafloor.

Finally, oceanographic conditions include a wide range of processes and properties associated with the water column including waves, currents (with a wide range of forcing functions), suspended sediment levels, water temperature, salinity and others.

Morphodynamic Impacts

The most apparent direct physical impact is the removal of substrate and the reduction in the elevation of the seabed. This may result in the creation of furrows or a pit or the removal of a bathymetric high such as the top of a shoal. Indirect morphodynamic impacts include subsequent changes to the seabed topography, seabed mobility, and shoreline change.

From a purely physical perspective, the only significant change of consequence is the potential indirect impact of dredging on shoreline change. For example, an increase in depth at a given location is not of direct importance to human activities, nor is a temporary sediment plume located in federal waters some distance from shore. Theoretically the shoreline change can occur in one of two ways: 1) through alterations to the wave transformation pattern, changing the waves that reach the shore, in turn modifying the sand transport-related processes and ultimately changing erosion and accretion patterns; and 2) by interrupting or modifying a sand supply pathway from or through the borrow area to the shore. A review of the currently identified OCS borrow deposits suggests that most, but not all, are immune from the second impact because they are isolated from the sediment budget of the littoral system by large distances and muddy areas (the latter indicating the absence of a sand transport pathway). Nevertheless, this will not always be the case. Careful consideration must be given on a site-specific basis to the possibility of interrupting a sediment supply pathway to the shoreline.

All other local physical changes and direct impacts caused by dredging are important only if they result in a biological impact, either directly or indirectly. From a morphodynamic perspective, the direct impacts consist of the depressions, furrows, and pits left by the dredging operations. Clearly, these can have an important impact on the benthic community. The indirect biological impacts derived from a change to morphodynamics may include long-term changes to depths within and beyond the dredge area, changing the mobility of the sediment due to a change in depth and/or wave conditions. Probably the biggest concern is the potential for ridge and shoal type features to deflate or be smoothed out where borrow deposits are accessed on an ongoing basis. This outcome could lead to large-scale impacts to biological communities that rely on the structure of these features and to possible shoreline impacts.

Impacts to Seabed Characteristics

Direct impacts to seabed characteristics include removal and disturbance of the substrate and exposure of an underlying layer with different characteristics (*i.e.,* grain size, reduced dissolved oxygen levels, and compaction), and changes in grain size of surficial sediments due to settling of fines from overspill plumes or sediment reworking. Indirect impacts include changes related to erosion and deposition. These changes to the seabed characteristics will only be significant where they result in biological impacts.

Oceanographic Impacts

The primary direct impact to the oceanographic conditions would be the elevated levels of suspended inorganic and organic solids in the overspill (at the point of discharge from the hopper dredge) and benthic (at the drag head) plumes. Indirect impacts include changes to the waves within and beyond the borrow area, changes to bed shear stresses and related seabed mobility due to changes to waves, and changes to near-bed current velocities driven by tides, wind, and large-scale phenomenon. Recent studies in the UK described by NEWELL *et al.* (1998) have found that the only detectable plume impact from a biological perspective is the direct sedimentation footprint and that this footprint is relatively limited in spatial extent (300 to 500 m from the borrow deposit). The potential biological effects of turbidity plumes on nekton include feeding impairment, a reduction in reaction distances (VINYARD and OBRIEN, 1976), reductions in the ability of visual predators to perceive and capture prey (BENFIELD and MINELL, 1996), and the clogging of gill cavities that results in retardation of normal respiration (BRUTON, 1985) and possible death (ROBINS, 1957). Based on the spatial and temporal extent of turbidity plumes from sand dredging operations, these impacts have been predicted to be insignificant (HAMMER, 2000). The investigations reported and referenced by NEWELL *et al.* (1998) pertain to heavily screened hopper dredge operations where there is a very significant overspill of sediment. Most sand dredging operations on the OCS will be non-screened (at least initially for beach nourishment borrow deposits) with much less overspill of sediment and the plume impact will be even less important than observed by NEWELL *et al.* (1998).

Biological Ecosystems

As illustrated in Table 1, the marine biological communities and associated habitats that were determined as being potentially affected by OCS sand dredging included: plankton, soft and hard substrate benthic communities, nekton, and marine mammals and wildlife.

As previously discussed, the MMS determined that hard substrate areas would be avoided by dredging activities or be surrounded by sufficient buffer zones to prevent dredge discharges from having any impact. In addition, since no sorting of dredged material would occur during beach replenishment dredging operations, the sediment plumes created by the dredge operations were determined to be very small and temporary. Consequently, effects to plankton, fish, and marine mammals should be minimal and of short duration (HARDAWAY *et al.,* 1998; HAMMER *et al.,* 1993).

Although short-term loss and changes in benthic community structure have been documented following sand dredging (BLAKE *et al.,* 1996; VAN DOLAH *et al.,* 1992), the ecological significance to the benthic community is uncertain. Studies investigating the recovery of benthic communities following dredging (BLAKE *et al.,* 1996; NEWELL *et al.,* 1998; VAN DOLAH *et al.,* 1992) have indicated that communities of comparable total abundance and diversity can be expected to recolonize dredge sites within several years. Although these recolonized communities may be similar in total abundance and species diversity, their taxonomic composition is often very different from pre- to post-dredging.

The key ecological question that remains to be answered is: Do the new benthic communities fill the same trophic function and provide the same energy transfer to higher trophic levels, as did the original communities? If they do not, then the potential long-term and cumulative ecological impacts of sand dredging may be far greater than predicted to date, a condition that may be unacceptable as more sites along the coast are dredged and others are dredged on a regular basis.

The potential direct effects to fisheries from sand dredging are unknown. Most of the environmental impact assessments prepared for OCS sand dredging indicate minimal or nonexistent impacts to fisheries (HAMMER, 1993; LOUIS BERGER GROUP, 1999). This assessment has been based on the determination that most of the fish inhabiting the potential dredge areas were characterized as wide-foraging or migratory, spending only part of their life cycle in the dredge borrow area. In addition, the ridge/shoal and shelf features identified as potential sand borrow areas are very large in geographic extent, extending over kilometers of seafloor, and the potential borrow area for each dredging event is relatively small. Therefore, the lost or altered habitat area, overall, would probably be minimal and very short-lived assuming that dredging technology is utilized that minimizes sediment plumes and sedimentation in surrounding areas.

We found that little is known or published on the ecological utilization of ridge/shoal features by fish. Whether these features provide critical habitat for spawning, overwintering, or foraging is relatively unknown. This information gap was identified as an area requiring further study, and the results from such a study could result in the modification of the proposed monitoring program.

Excluding the potential effects of lost essential habitat as a result of dredging, the greatest potential effect to the fish community utilizing a dredge borrow area is an alteration in trophic energy transfer from the benthos to the fish popula-

Table 1. *Summary of potential physical and biological effects of OCS sand mining for beach replenishment.*

	Physical or Biological Change	Effects/Impacts
Morphodynamics		
Direct	Creation of depressions and furrows (possibly ≥1 meter) from removal of substrate	Could result in changes to dredge site and shoreline geomorphology Potential change to benthos
Indirect	Change to seabed topography beyond immediate dredge area through induced erosion/deposition (created by changes to sediment transport processes and pathways)	Could result in impact (long-term) to shoreline geomorphology or the unraveling of a shoal/ridge feature Potential change to benthos
	Change to seabed mobility due to change in depth and in waves/currents (driving forces)	No known or identified significant physical impacts other than those that result in biological impacts. Potential change to benthos
	Change to shoreline evolution	Altered shoreline dynamics
Seabed Composition		
Direct	Removal (and disturbance) of substrate and exposure of underlying layer with different characteristics (grain size, DO, compaction and organic content). In some cases that may result in a positive impact where preferred substrates are exposed.	No known or identified significant physical impacts other than those that result in biological impacts. Potential change to benthos and indirectly to nekton and marine wildlife
	Change in grain size due to settling and deposition of sediment in overspill plume (inside and outside dredged area) and creation of trap for finer sediment.	No known or identified significant physical impacts other than those that result in biological impacts. Potential change to benthos (smothering and altered habitat)
Indirect	Changes in grain size, compaction, organic content and DO induced by indirect erosion/deposition	No known or identified physical impacts. Potential change to benthos and fish (altered habitat)
Oceanography		
Direct	Elevated levels of suspended inorganic and organic solids in the overspill and benthic plumes	Temporarily increased water column turbidity Minimal effect to plankton, marine mammals, marine wildlife and nekton
Indirect	Changes to wave climate over and inshore of the borrow area	Could result in changes to shoreline geomorphology (long-term) to or the unraveling of a shoal/ridge feature Potential change to benthos
	Changes to shear stresses related to alterations to the wave climate	No known or identified significant physical impacts other than those that result in biological impacts.
	Changes to near bed current velocities associated with tidal, density driven and large scale circulation	Could result in shoreline geomorphology impact (long-term)
Geography (location of the borrow deposit)		
Direct	None	No known or identified physical impacts
Indirect	None	No known or identified physical impacts
Plankton		
Direct	Short-term Increased turbidity from cutter head or dredge barge overspill	Limited reductions in primary and secondary productivity
Benthos		
Direct (Soft Bottom)	Loss or reduced suitability of habitat	Total removal/loss of infauna and epifauna at borrow site with recolonization by benthic organisms occurring within 1–5 years (possibly longer) to a community with comparable predisturbance abundance, diversity and biomass but different species composition and community structure
	Changes in nearfield habitat condition resulting from altered sediment particle size composition from cutter-head discharge or altered ridge morphology	Changes species composition and community structure (species present, diversity, abundance and biomass) in nearfield areas
Direct (Hard Bottom)	Increased deposition of advected suspended sediments, increased fluxes of suspended sediments during dredging	Burial of near-bottom organisms with potential changes in species composition and community structure, fouling of feeding and respiratory surfaces
Indirect (Soft Bottom)	Recolonization by an altered (different species composition and community structure) biological community	Altered productivity and energy transfer effects on the food chain; altered species composition of fish prey base
Indirect (Hard Bottom)	Recolonization by an altered (different species composition and community structure) biological community	Altered productivity and energy transfer effects on the food chain; altered species composition of fish prey base

Table 1. *Continued.*

	Physical or Biological Change	Effects/Impacts
Nekton		
Direct	Loss or reduced suitability of habitat	Removal of infauna and epifauna: 1) Loss of foraging habitat; 2) Loss of spawning habitat; 3) Loss of over-wintering habitat
	Increased turbidity and sedimentation	Low risk of gill clogging and burial
Indirect	Recolonization by an altered (different species composition and community structure) biological community	Altered foraging efficiency with resultant effects on individual size, weight, and fecundity
Marine Mammals & Wildlife		
Direct	Collisions during dredging operations and some noise disorientation.	Injury or death of animal; potential disorientation
	Loss or reduced suitability of habitat	Removal of infauna and epifauna: Change in foraging area and food
Indirect	Nearfield habitat changes	Removal of infauna and epifauna: Change in foraging area and food
	Increased turbidity and sedimentation	Reduced visibility resulting in reduced foraging efficiency and injury for visual predators

tion. As indicated above, if the post-dredging amount of energy being transferred to fish populations from the benthos is less than the pre-dredging energy transfer, then the potential long-term and ecological impacts of sand dredging may be far greater than predicted to date, and the level of impact may become unacceptable as more sites along the coast are dredged and others are dredged on a regular basis.

Direct and indirect impacts to marine mammals and other marine wildlife (*e.g.,* sea turtles and birds) were also assessed. The only identifiable direct effect from sand dredging is associated with the direct collision of marine mammals and turtles with the dredge ship or the entrainment of turtles in the suction dredge. Although such occurrences are very rare, U.S. environmental regulations mandate that any potential negative interactions with marine mammals and turtles should be prevented.

LONG-TERM MONITORING PROGRAM DESIGN

All of the identified OCS borrow sites share some common features. They are all in relatively shallow water, generally between 5 m and 15 m deep. The sites are mostly disconnected from coasts with respect to sediment transport pathways. The sites also fall into three morphologic categories: isolated ridges and swales, shoals, and shelves. Most of the sites that have been identified thus far fall into the ridges and swales category. These features are described in more detail in a companion paper included in this special issue (Hayes and Nairn, 2004). It is noted that there are likely to be many other deposits discovered in the future that are associated with buried paleo channels and deltas. While more difficult to identify initially, these types of features may provide better quality sand, be located closer to shore, and may have less potential for impact when dredged. The monitoring program developed for the MMS is capable of addressing all types of borrow deposits.

Following the evaluation and assessment of physical and biological impacts that potentially result from OCS sand mining, six elements were selected for inclusion in the monitoring program. They included: sediment sampling and analysis, wave monitoring and modeling, bathymetric and substrate surveys, shoreline monitoring and modeling, benthic communities and their trophic relationships to fish, and marine mammals and wildlife.

Physical Monitoring Elements

Recognizing the fact that most physical impacts have the potential to become significant only when they result in unacceptable direct or indirect biological impacts or affect shoreline dynamics, inshore of the borrow deposit, the monitoring program needed to consider the biophysical interactions of the physical impacts. The review of possible physical impacts resulting from sand dredging indicated that for monitoring and modeling of physical parameters, only three physical changes needed to be considered. These included, changes to bathymetry, changes to waves and possible related shoreline changes, and changes to the seabed characteristics that may result in biological impacts. Based on these considerations, four physical monitoring and modeling protocols were developed to address these issues, which included bathymetric and substrate surveys, sediment sampling and analysis, wave monitoring and modeling, and shoreline monitoring and modeling.

The first two protocols primarily address the potential for biological impacts that may result from physical impacts. They essentially focus on tracking geomorphic changes to the borrow area and the surrounding seabed. For many of the currently identified OCS deposits, the potential impacts to the form of ridge and shoal features will be closely monitored. The bathymetric and substrate surveys protocol also provides a description of the form of the borrow deposit (and any indirect changes on adjacent seabed elevations) that is required as input to the Wave Modeling, the third protocol listed above.

The third and fourth protocols listed above address the potential for shoreline impacts that may be directly related to changes to the seabed elevations in the vicinity of the borrow deposit. Changes in seabed elevations may, in turn, influence the waves that reach the shore inshore of the borrow deposit,

Table 2. *Summary of requirements of the physical monitoring protocols.*

Protocol	Potential Impact	Objectives	Requirements: Monitoring	Requirements: Modeling
Bathymetry and Substrate	Changes to the morphology and substrate characteristics of the borrow deposit and surrounding area (particularly for ridges and shoals) and potential physical (waves and shoreline change) and biological impacts.	1. Determine the location and quantity of sand removed and change to bathymetry caused by dredging operations. 2. Quantify subsequent changes to bathymetry in the immediate vicinity of the borrow area. 3. Quantify potential changes to the overall borrow deposit feature (e.g. ridge or shoal if one exists)	1. Hydrographic Survey (single beam acoustic) plus Side Scan Sonar: or, 2. Hydrographic Survey with Multibeam technique; or, 3. LIDAR/SHOALS or other methods that are able to achieve specifications and requirements of the Protocol. Limitations of LIDAR/SHOALS for this application are detailed in Michel et al. (2001).	
Sediment	Changes in sediment texture and total organic content and subsequent biological impacts.	1. Define changes to texture caused by removal, sedimentation and indirect erosion/deposition processes. 2. Potential changes may serve the assessment of changes to morphology of features at the borrow deposit (e.g. ridges and shoals). 3. Determine changes in TOC to assess potential impact to benthic communities.	Collect sand samples at the location of benthic samples and test for grain size distribution (both sieve and hydrometer test or equivalent) and TOC method based on high temperature combustion.	
Waves	Change to wave transformation patterns over the dredged area with possible ultimate impact of shoreline change	1. Develop a continuous record of wave conditions starting from first access of borrow deposit. 2. Assess influence of initial changes to bathymetry. 3. Assess influence of subsequent (direct and indirect) changes to bathymetry.	Deepwater (or preferably directly offshore of the borrow site) wave data through combination of measured directional data and nondirectional data and available hindcast data.	Complete nearshore wave transformation modeling to transfer deepwater waves to the borrow deposit (if necessary), over the borrow deposit and into shore (ultimately for input to the shoreline change model).
Shoreline	Shoreline erosion directly attributable to dredging at the borrow deposit.	1. Document actual shoreline change (regardless of cause). 2. Assess the impact of dredging at the borrow deposit.	1. Beach and Nearshore Profile Surveys twice per year every 300 m. 2. Georegistered aerial photographs and digitized shoreline twice per year.	Apply GENESIS model or equivalent to assess longshore sand transport and related shoreline change with and without project prior to and after dredging commences (comparing to measured change in latter case).

and such changes to waves change longshore and cross-shore sand transport rates and the resulting shoreline dynamics. Because there are many other factors that may result in changes to shoreline dynamics, the Wave and Shoreline Protocols include two important and distinct features: 1) documentation of waves and shoreline change as a record of conditions; and 2) the need for modeling, in addition to monitoring, to attempt to isolate the direct influence of the changed bathymetry near the borrow area on waves and shoreline dynamics (*i.e.* from all the other possible factors that may influence these processes). While it is recognized that numerical modeling of these complex processes has many limitations, these techniques provide at least some insight into the processes and the potential for dredging to lead to shoreline changes. Recommendations for specific models, their limitations and background references are provided in MICHEL *et al.* (2001). Taken together with the field data derived from the monitoring and an understanding of the geomorphology of the area, the numerical model results provide the basis for evaluating the potential impacts of dredged borrow deposits on shoreline dynamics.

The four physical monitoring protocols are summarized in Table 2. This table provides the key potential impact, the monitoring objectives, and the monitoring and modeling requirements of each of the program elements. This table is provided as an overview only and the information is not intended to provide a complete guideline for the monitoring requirements. Detailed procedures are contained in MICHEL *et al.* (2001).

Detailed monitoring of the plumes generated during dredging operations at the overspill point and the draghead has not been included as a requirement because the primary concern is the extent of the sedimentation footprint, not the impact of the temporary plume itself. The extent of the sedimentation footprint will be documented by the sediment sampling program where the substrate has changed significantly with respect to grain size. *A priori* knowledge of the extent of the footprint would be useful to develop the spatial boundaries for the monitoring programs. This is the focus of a Plume Model development and testing project currently being undertaken by MMS in FY02. The Plume Model will also be useful for assessing future aggregate dredging operations that often rely on heavy screening that produces much larger plumes.

Biological Monitoring Parameters

Based on the potential direct and indirect effects to marine biota from sand dredging activities, the biological monitoring elements of the MMS OCS sand mining monitoring program focused on benthic communities and their trophic relationships to fish, and marine mammal and wildlife interactions with dredging operations. The biological monitoring program design further focused on long-term rather than short-term impacts and ridge and shoal type ecosystems, because of their greater micro-habitat and geomorphological complexity. The proposed protocols and monitoring program design are equally applicable to flat, shelf-type ecosystems where buried geological features can represent suitable sand and gravel borrow deposits.

Potentially, the most obvious biological effect of sand dredging operations is the complete removal of soft bottom habitat along with resident benthic organisms within the dredge area. Such removal affects not only the benthic communities, but also the fish assemblages that rely on the benthos for food. In addition, the potential small- and large-scale changes to seafloor geomorphology (*e.g.,* substrate type and composition, surface texture, water circulation, nutrient distribution) due to altered wave patterns and sediment transport in the vicinity of the dredging operation (Figure 1) may also affect benthic community structure and trophic energy flow.

The recommended approach for monitoring biological change, therefore, involves measuring trophic energy transfer between the benthos and representative species of the fish population. This approach facilitates the monitoring of changes over a very wide area of potential impact, as well as changes resulting from the sand dredging operations, regardless of the origin of the habitat change (*e.g.,* direct removal of sand or potential changes in habitat sediment composition following geomorphological changes in the ridge and shoal or shelf structure). In addition to measuring trophic energy transfer effects, limited community structure and composition information would be gathered on the benthos and fish. This focused approach has the added benefit of improving cost effectiveness.

Monitoring dredging effects on trophic transfer would be accomplished through sampling benthic and fish communities for the numbers and species of organisms present. Numerically dominant and recreationally or commercially important species would receive additional investigation. These species would be analyzed for stomach contents to determine their utilization of benthic organisms. The utilized benthic species would be analyzed for their estimated secondary production using models developed over the past 20 years (Maslin and Pattee, 1981; Morin and Bourassa, 1992; Tumbiolo and Downing, 1994). The amount of benthic production that is transferred to fishes would be estimated using accepted trophic transfer efficiencies and differences between dredged and reference areas in the benthic production that is transferred to fishes will be determined statistically. Stable isotope analyses also will be performed on benthic prey species and fishes to determine whether altered secondary production and trophic transfer associated with dredging affects the trophic level at which fishes feed.

Stratification is an important strategy for sample allocation that would be used to improve the ability of the biological monitoring program to detect impacts. Strata would be identified based upon factors that are known to affect the distribution and abundance of organisms in the target communities. Pre-dredging samples would be collected from within strata (*i.e.,* areas) that are as physically homogeneous as possible. Impacts and recovery would be inferred by differences in temporal trends or changes in biological similarity (*e.g.,* secondary production) between dredged and control areas within strata.

Several factors are known to affect the distribution of benthic species and these should be considered in determining the pre-dredging strata. Sediment grain size and organic content are among the most important factors controlling the distribution of benthic organisms (Brown *et al.,* 2000; Grove and Probert, 1999; Mancinelli *et al.,* 1998; McLachlan, 1996; Pearson and Rosenberg, 1987; Rosenberg, 1995). These factors, which vary with depth, also can be affected by bottom topography and water motion (Tanaka and Dang, 1996). The selection of strata for benthic sampling should be based on site-specific evaluations of these factors, as well as the morphology of the sand deposit to be dredged. Sand ridges should be divided into strata of offshore ridge slope, ridge crest, nearshore ridge slope, and swale bottom, at a minimum. If the ridge is large enough or nearby seabed features are near enough and large enough to affect lengthwise heterogeneity in the sediment grain size and organic content, then additional strata should be designated. If sufficient data to designate strata are not available prior to the pre-dredging sampling, then additional sampling will be necessary to obtain these data. Although fish are more mobile than benthic organisms and may move between strata, they should be sampled within the same strata defined for the benthos. Maintaining consistent strata for benthic communities and fish assemblages will improve the ability to correlate benthic organisms with fish.

To provide a balanced statistical design, defined strata should be present in both the dredged area and the control areas. The control area should be near the dredged area to ensure similarity of factors such as depth and wave regime, but removed far enough to minimize dredging effects. The ideal proximity between dredged and control areas will depend on site-specific conditions, such as depth and the amount of area being dredged. Delineation of strata and subsequent sampling should ensure the same sample density in both dredged and control areas. To satisfy this requirement, the areas of sampling strata in dredged and reference areas should be approximately equal. Moreover, there should be assurance that reference areas will not be subjected to dredging before the completion of monitoring at that site.

The sampling design involves collection of samples before and after each dredging operation over multiple years (years 1, 3, 5, and 7) in areas that were physically similar before dredging. Because initial successional processes may affect the rate and process of long-term recovery in dredged areas, the first post-dredging survey should be conducted one year following dredging. In addition to the pre-dredge survey, a baseline survey may also be required if sufficient data are not available for strata delineation.

The principal purpose of the baseline survey would be to obtain sufficient information about the borrow site and adjacent areas to effectively delineate benthic habitats. This baseline survey can be accomplished using Sediment Profile Imaging (SPI) equipment (CUTTER and DIAZ, 2000a; CUTTER *et al.*, 2000b) or benthic grabs. The effort can be combined with baseline geophysical data gathering efforts. At a typical ridge/shoal feature, this effort would include delineating the seaward flank of the feature, the landward flank and the ridge top, at a minimum, at both dredge and control locations. For a shelf feature, depth stratification may be more important.

As far as possible, sampling should be conducted in the same season for both pre-dredging and post-dredging sampling. Benthic communities exhibit strong seasonal patterns (OTT and FEDRA, 1977; SARDA *et al.*, 1999; VALLETT and DAUVIN, 1999) and maintaining seasonal consistency of sampling reduces the effects of season on detection of long-term trends and recovery from dredging. It is suggested that summer is the best time to conduct sampling (ALDEN *et al.*, 1997). These investigators found that summer sampling provides the greatest power for detection of trends and that differences in benthic response between reference and degraded sites are greatest in summer. Nevertheless, temporal proximity of sampling to dredging is more important than blindly requiring sampling to be conducted in the summer. Benthic sampling can be done concurrently with fish sampling or during a separate survey leg.

Scientific rigor should be incorporated into the monitoring program through several approaches. First, as mentioned above, sampling sites should be distributed among strata based on environmental variables known to influence communities. This will reduce within-treatment variation and improve statistical power. Second, the sampling design should utilize statistical tests and interpretive criteria to minimize misidentification of dredging impacts. The recommended sampling design is amenable to comparisons of variation within and between treatments through analysis of variance (ANOVA) and also to various multivariate approaches. Using ANOVA, dredging effects would be ascribed to significant time and treatment interactions that correspond to a divergence between dredged and undredged areas at the time of dredging. Recovery would be ascribed to a reconvergence between dredged and undredged areas over time. Ancillary physical data and species data would provide variables for multivariate analyses. Third, while the objective of the biological monitoring protocols is to estimate changes in secondary production and trophic transfer from benthos to fishes and not detailed descriptions of the communities, numbers of replicate samples would be based upon statistical characteristics of the biological communities, such as minimization of standard error. Such an approach would ensure representative abundance estimates and descriptions of the communities for use in estimating changes in secondary production and trophic transfer.

In addition to monitoring effects on trophic energy transfer, the potential physical interactions and impacts to marine mammals and wildlife also would be monitored. This element of the monitoring program is addressed as an operational control and monitoring component, that occurs during the dredging operations. During dredging activities, marine wildlife observers would be placed aboard the dredge vessel or an ancillary craft to observe the presence of marine wildlife in the dredge area. The observers would document the behavior of marine wildlife in response to the dredging activities, and document any collisions or other negative interactions between the dredge vessel and support craft with marine wildlife.

Finally, concurrent with the sand dredging operations and for a period of 60 days after completion of sand dredging, marine wildlife observers would be in communication with federal, state and local agencies responsible for documenting marine wildlife strandings. Every reported stranding that occurs along the coastline adjacent to the dredging operations would be checked for possible correlation with animals observed during the dredging operation (species, size, unique body markings, etc.) and for possible new markings on the body that would suggest a collision with the dredging equipment.

A summary of the two biological monitoring protocols is presented in Table 3. This table provides the key potential impact, the objectives, and the monitoring and analysis requirements of each of the monitoring program elements. This table is provided as an overview only and the information is not intended to provide a complete guideline for the monitoring requirements, which are detailed in MICHEL *et al.* (2001).

ADAPTIVE MANAGEMENT

A key component of any long-term scientific study or monitoring program is the need to adapt the original study design and approach to reflect information and understanding gained during the execution of the program. For this reason, it was recommended that the MMS will establish a permanent scientific review/advisory board to oversee the implementation and future revision of the OCS long-term sand monitoring program and advise the MMS on the program components. Another important responsibility of the scientific advisory board would be to ensure the scientific validity and integrity of individual borrow site monitoring programs and their findings.

CONCLUSIONS

Review of the literature and assessment of the inter-relationships between biological and physical parameters and

Table 3. *Summary of requirements of the biological monitoring.*

			Requirements	
Protocol	Potential Impact	Objectives & Justifications	Monitoring	Analysis
Benthos and Fishes; Trophic Transfer	1. Total removal/loss of infauna and epifauna at borrow site with recolonization by benthic organisms occurring within 1–5 years (possibly longer) to a community with comparable pre-disturbance abundance, diversity and biomass but different species composition and community structure 2. Altered foraging efficiency with resultant effects on individual size and weight. 3. Altered species composition of fish prey base; altered productivity and energy transfer effects on the food chain	1. To determine the effects of dredging activities on benthic communities and the transfer of energy from benthic communities to fishes. While overall abundances of benthic organisms have been shown to return to pre-dredging levels in some cases within year or two after dredging, species composition may be different and the ability of fishes to utilize such altered assemblages for prey is uncertain	1. Collect 0.10 m^2 benthic infauna samples from multiple strata at both impact and reference locations prior to dredging and in years 1, 3, 5 and 7 following dredging. Monitoring may cease when recovery has been documented 2. Collect stomachs from numerically dominant or recreationally important species from multiple strata both impact and reference locations prior to dredging and in years 1, 3, 5 and 6 following dredging.	1.a. Infauna taxonomy for comparison with fish gut contents analysis and for determining secondary productivity values. 1.b. Biomass measurements for determining secondary productivity values. 1.c. Carbon and nitrogen stable isotope measurements of key benthic prey species for fish. 2.a. Fish gut analysis for comparison with infauna taxonomy. 2.b. Carbon and nitrogen stable isotope measurements of fish muscle tissue.
Marine Mammals & Wildlife	Injury or death of animal; potential disorientation	1. To obtain site-specific marine wildlife observation and behavior data during OCS dredging events. This information will assist state and federal regulatory agencies in assessing the appropriateness of imposed marine mammal and wildlife protection mitigation requirements and guide any necessary revisions of future mitigation requirements. 2. To obtain and assess marine wildlife stranding data for potential relationships between stranded animals and animals observed during OCS dredging. This information will assist state and federal regulatory agencies in assessing whether there exist any obvious relationships between post-dredging marine wildlife strandings and the OCS dredging event 3. To provide a means for implementing environmental mitigation requirements designed to minimize potential hazardous interactions with marine mammals and protected wildlife during dredging events. (This is the only "operational control" monitoring program element included in the OCS and dredging protocols.)	1. Collect observation and behavior data onboard the dredging vessel for marine mammals and wildlife during OCS dredging events. 2. Collect marine mammal and wildlife stranding data for a 60-day period following dredging operations. 3. Implement imposed environmental mitigation requirements designed to minimize collisions or harmful interactions between marine wildlife and dredging equipment.	1. Compare observation data with stranded animal data and document marine wildlife behavior during dredging events. 2. Compare marine wildlife data with observation data collected during the dredging event as well as with stranding data recorded for comparable time periods during nondredging years.

processes indicated potential significant impacts of dredging on the outer continental shelf. The protocols were designed to monitor the significance of these key impacts.

The two primary impacts of concern for the physical environment are indirect and related to: changes to the seabed that would result in changes to the erosion and sedimentation processes along the shore; and changes to the seabed at or inshore of the dredge area that would have a direct and significant impact on the benthic biological communities and their trophic energy transfer to fishes.

Impacts to shoreline change will be very difficult to discern from the existing temporal and spatial variability in shoreline erosion and sedimentation. Therefore, the protocols are based on an approach that will develop the necessary information to explain the relative influence of the changes caused by dredging. The approach relies on the surveying of changes to the seabed in the vicinity of the borrow deposit together with monitoring of waves, wave transformation modeling, and shoreline change monitoring and modeling.

With respect to the possible influence on the biological communities, one of the greatest concerns identified was the impact that dredging may have on the maintenance of the future form of ridge and shoal features. Little is known about the processes that maintain these features on the outer continental shelf. The companion paper in this issue by HAYES and NAIRN (2004) discusses this issue. Where pronounced, the form of the ridge and shoal features provides for different habitat conditions in terms of sediment type and mobility and a related patchwork of different biological assemblages. The concern is that too much dredging off the crest of one of these ridges could result in dramatic deflation of the feature and the loss of habitat. The monitoring protocols have been designed to track the ongoing and long-term changes to the form and surface texture of these features resulting from single event and repeated dredging of these features. The developed protocols will provide an effective form of monitoring for all types of seabed morphology.

One potential physical impact that has not been directly targeted for monitoring as part of the protocols relates to the sediment plume generated by the hopper dredging operations. The sedimentation footprint of the plume, where discernible, will be elucidated through the sediment sampling program. There is general agreement in the literature that increased turbidity levels do not lead to significant impacts in typical outer continental shelf conditions. Where local conditions dictate, such as proximity to hard substrate that cannot tolerate any level of sedimentation, a more detailed assessment will be required. In all of the borrow sites identified to date, on the outer continental shelf of the Atlantic and Gulf coast of the U.S., this was not found to be an issue of concern. MMS is currently funding the development of a plume dispersion model specifically designed for the loading of hopper dredges to provide a tool to better define these impacts in the planning stages of projects. Once developed, the model will also assist in the development of the spatial layout of sediment and benthic sampling.

The most direct impact of sand dredging on biological communities involves removal of benthic biota. Previous studies have shown recovery, usually within three years, of the numbers of species and numbers of organisms, although the species colonizing dredged areas may differ from those that were present before dredging. The apparent absence of data for changes in trophic transfer from benthos to fishes associated with the altered, post-dredging benthic communities suggested the importance of monitoring the affects of changes in benthic secondary productivity on fish production.

Changes in fish production will be estimated by sampling benthic organisms within defined strata, both inside dredged areas and at nearby reference areas, before and after dredging. Published models will be used to estimate the secondary production of those benthic species that are important prey items for fishes, as determined by analysis of contemporaneous fish gut contents. Temporal changes in benthic secondary production that differ between dredged and reference areas will be converted to corresponding changes in fish production using accepted figures for the efficiency of trophic transfer. Changes in trophic transfer of benthic secondary production will be compared with stable isotope analyses to determine whether altered secondary production and trophic transfer affect the trophic level at which fishes feed.

A study design has been recommended that will utilize statistical tests and interpretive criteria to minimize misidentification of dredging impacts. Comparisons of variation would be made within and between treatments (*i.e.,* dredged and undredged) through analysis of variance (ANOVA). Dredging effects would be ascribed to significant time and treatment interactions corresponding to a divergence between dredged and undredged areas at the time of dredging in benthic secondary production and trophic transfer from the benthos to fishes. Recovery would be ascribed to a reconvergence between dredged and undredged areas over time.

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